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Optical Switching and Optical Logic in a Thermally Expanding Si Etalon

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Abstract

Optical switching in a thermally expanding Si etalon has been demonstrated. In this experiment a pulsed CO₂ laser beam is used to heat a Si etalon and shift the interference fringe of a 1.5 μm probe beam. It is shown that the switching time can be greatly reduced from ms to μs by choosing a probe beam of shorter wavelength in an external switching configuration. By aligning one etalon at switch-on and another at switch-off, we demonstrate a write and erase logic system.

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Since the first observation of optical bistability in a silicon etalon using $1.06\text{ }\mu\text{m}$ laser radiation¹, the experimental efforts have been directed to reduce the switching power and switching time. The Si Self-Electro-Optical-Effect-Device (SEED) has recently been shown to greatly reduce the threshold input power at which bistability can occur². The Si etalon operating in the lattice vibration region ($10\text{ }\mu\text{m}$) has also been experimentally realized as an optical bistable device³. The switching times of these thermooptical devices, however, are slow. They are all in the range of ms which is about the thermal relaxation time.

In this letter we report the external switching of $1.5\text{ }\mu\text{m}$ IR light from a thermally expanding Si etalon. By using 100 ns CO_2 pumping pulses, we observed the switch-on and -off time of $\sim 1\text{ }\mu\text{s}$, which is much faster than the thermal relaxation time. The switch-on or -off condition depends on the initial phase of the etalon, i. e. the alignment of etalon with the incident light. This feature of reversible switching has been utilized to perform "write and erase" optical logic.

CO_2 laser light operating at a wavelength of $10\text{ }\mu\text{m}$ is near the edge of the silicon lattice vibration absorptions. The power dissipated in a Si etalon for $10\text{ }\mu\text{m}$ radiation would cause thermal bistability in the transmission and the reflection light³ where self-switching was observed when the Si etalon was illuminated by only the CO_2 $10\text{ }\mu\text{m}$ light. A cw CO_2 laser was pulsed using an electronic shutter with a pulse duration of around 100 ms. The reflection from the Si was detected as shown in Fig.1. Several orders of nonlinear reflection appear as the incident power is increased to a peak power of $\sim 1\text{ w}$. The etalon self-switched at a power as low as a few mw.

A simple expression for the mechanism of this dissipative thermally expanding etalon can

be given by considering that the transmission maximum or reflection minimum occurs at the interference resonance condition given by:

$$2nL\cos\theta = m\lambda \quad (1)$$

where n , L , and θ are refractive index of the cavity material, cavity length, and incident angle, respectively, and m is an integer. The dissipative energy inside the cavity generates heat, ΔT , which causes the thermal expansion of the cavity, i. e. change L . The cavity length is thus given by

$$L = L_0 + \alpha\Delta T \quad (2)$$

where α is the thermal expansion coefficient. Substituting equation (2) in equation (1), one sees that the resonance condition no longer exists, because L is a function of temperature. A phase change, $\Delta\lambda$, due to the thermal expansion of the cavity is given by

$$\Delta\lambda = 2n\alpha\Delta T\cos\theta \quad (3)$$

A phase change of half of a wavelength is required for a high contrast switching ratio.

The thermal expansion is an integrating effect, and the switching would not take place until the dissipative energy is sufficient to expand cavity by at least a half wavelength. Thus, for this kind of a device at a fixed incident angle, the incident wavelength would determine the switching time. This is so because a short wavelength would require less thermal expansion, hence less time, to switch. Due to its long wavelength, CO_2 laser light switched in the time range of ms. It is therefore expected that, at a fixed incidence angle, the shorter the wavelength the probe beam, the faster will be the switching time. However, the probe beam light must not be excessively absorbed by the etalon material.

The probe beam from a $1.5\text{ }\mu\text{m}$ cw HeNe laser was chosen so that in the absence of a pump beam the reflected amplitude of the probe beam is determined by tuning the incident angle of the Si etalon. The pump beam is from a pulsed CO_2 laser with a pulse duration of 100 ns. Efficient absorption of the pump beam energy enables the etalon to have a sufficiently large thermal shift in a short time, so as to yield a strong interference effect for the probe beam.

The etalons used are $2\times 2\text{ cm}$ n-type Si with resistivity $\sim 1\text{ }\Omega\text{cm}$ with 2 surfaces polished and with a thickness of $\sim 400\text{ }\mu\text{m}$. The Si etalon was aligned where reflection was minimum, i. e. transmission resonance, in order to enable the buildup of a coherent field inside the cavity. The incidence angle was slightly off the normal direction, to be sure that the angle did not severely reduce the phase change. The reflection of the $1.5\text{ }\mu\text{m}$ light was monitored by a germanium detector. Upon the illumination of the etalon by the pump beam, heating, expansion, and detuning occurred, resulting in a rapid increase of the reflected power from probe beam. The external switched out signal of $1.5\text{ }\mu\text{m}$ light is shown on Fig.2. It is noticeable that, the switching time was $\sim 1\text{ }\mu\text{s}$ which was faster by 3 orders of magnitude than self-switching CO_2 light. The switching ratio was $\sim 0.7:1$. Since the duration of the pump CO_2 laser is only 100 ns, energy integration requires a relatively higher pumping power. Experimentally, we measured the threshold switching power at $\sim 10\text{ kw}$.

Since the switching is based on the shift of an interference fringe due to the cavity expansion, it is predictable that one can obtain either a switch-on or switch-off signal by setting the etalon at the appropriate initial phase. When the etalon is aligned by tuning the incident angle to be a resonant position with reflection minimum, the pump beam will switch

the etalon off and obtain a higher reflection state as the cavity changes slightly by the pump beam. The switch-on is the opposite. The etalon is initially set in non-resonant position, but just off the reflection minimum, so that for a small change it will be switched-on. With the pump beam pulse, the reflection will decay rapidly. We have observed both switch-on and switch-off phenomena with similar switching times.

The capability of achieving reversible switching in the Si etalon provides a possibility to build a "write and erase" optical logic system. The experimental configuration is schematically shown on Fig.3(a). In the absence of a pump beam, etalon 1 was tuned at the resonant position, and etalon 2 was detuned to be just off resonance for the $1.5\ \mu\text{m}$ probe light from a cw HeNe laser. The reflected beam from etalon 1 was the holding beam for etalon 2. The pumping pulse from a pulsed CO_2 laser was split in two beams. One of the beams could be attenuated by adjusting the pressure of SF_6 gas in a transmission cell, so that the power of both beams could be balanced to obtain optical signal erasure. The $1.5\ \mu\text{m}$ probe beams reflecting from both etalons was serially monitored by the Ge detector. With the upper pump beam blocked only etalon 2 was switched-on, while etalon 1 served as a mirror. The oscilloscope trace shows a negative reflection signal coming from etalon 2. The positive and the negative signals from each etalon are shown in Fig.3(b). In the presence of both pump beams, etalon 1 was switched-off "writing" a positive reflection signal, while etalon 2 was switched-on "erasing" the signal from etalon 1. The amplitude of "writing" signal could be adjusted by controlling the power of the upper pump beam to obtain complete erasure as shown in Fig.3(c) which should be a flat baseline.

The reversible switching can also be utilized to clean the tail of a signal. If an optical

delay is added in the lower pump beam to delay the erasure of the positive signal, a square signal pulse at microsecond scale will result.

Equation (3) indicates that the phase change, $\Delta\lambda$, is proportional to the heat generated by the pump beam. Thus, an effort was made to investigate if there was pump power dependence of the on or off switching behavior, i.e. the possibility to shift the interference fringe by a variable order. For this experiment a Si etalon was initially set in a resonant condition and as the pump power increased, the positive reflection signal was observed to grow stronger. When a switching ratio of 0.7:1 was achieved, however, the signal did not increase further, and the etalon could only be switched-off whatever was the pumping power. This appears to result from saturation absorption of the CO₂ pump power by the Si.

In conclusion, we have demonstrated optical switching in a thermally expanding Si etalon. By using a shorter wavelength probe beam, we achieved a 1 μ s switching time compared with ms in previous work³. It has been shown that the switching time for this kind of etalon is not intrinsic but depends on the wavelength of the probe beam. The principle is general and should lead to the use of other materials for the etalon. The initial phase of the etalon tuned determines the switch-on or -off condition, and this has been utilized to perform "write and erase" optical logic. This kind of "write and erase" operation can be extended to parallel processing, that is, several signals can be processed on one optical device simultaneously, as long as the reverse switching exists in the device.

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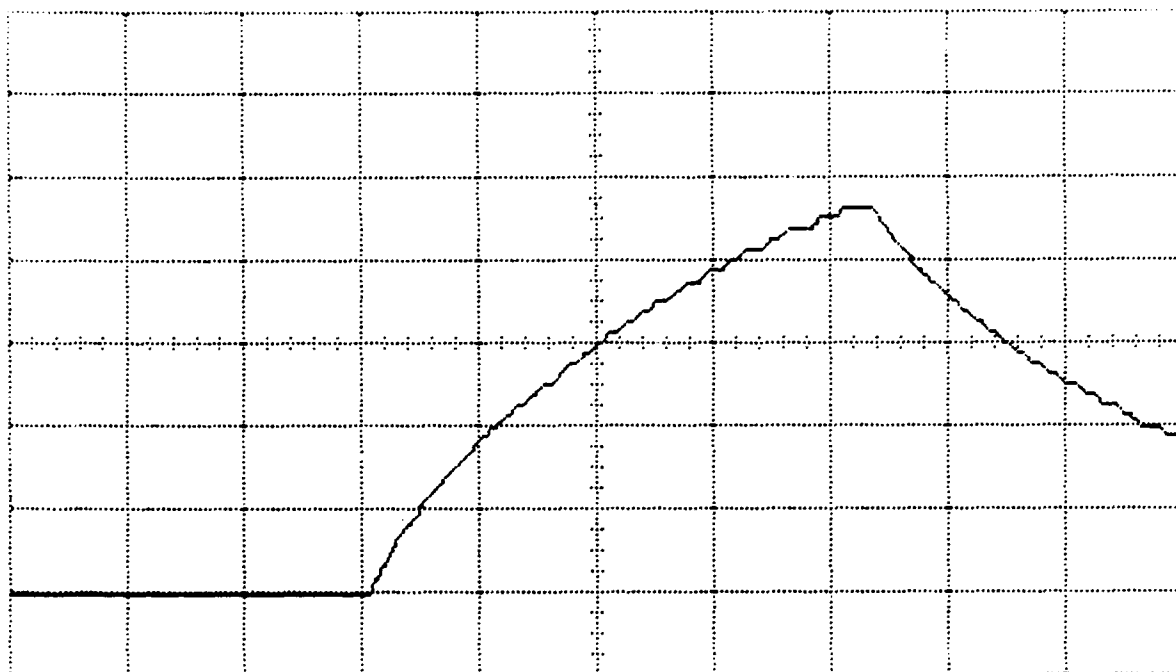
Captions

Fig.1 The reflection from a Si etalon showing self-switching: (a) incident CO_2 pulse, (b) reflected pulse.

Fig.2 Externally switched out signal of $1.5 \mu\text{m}$ light.

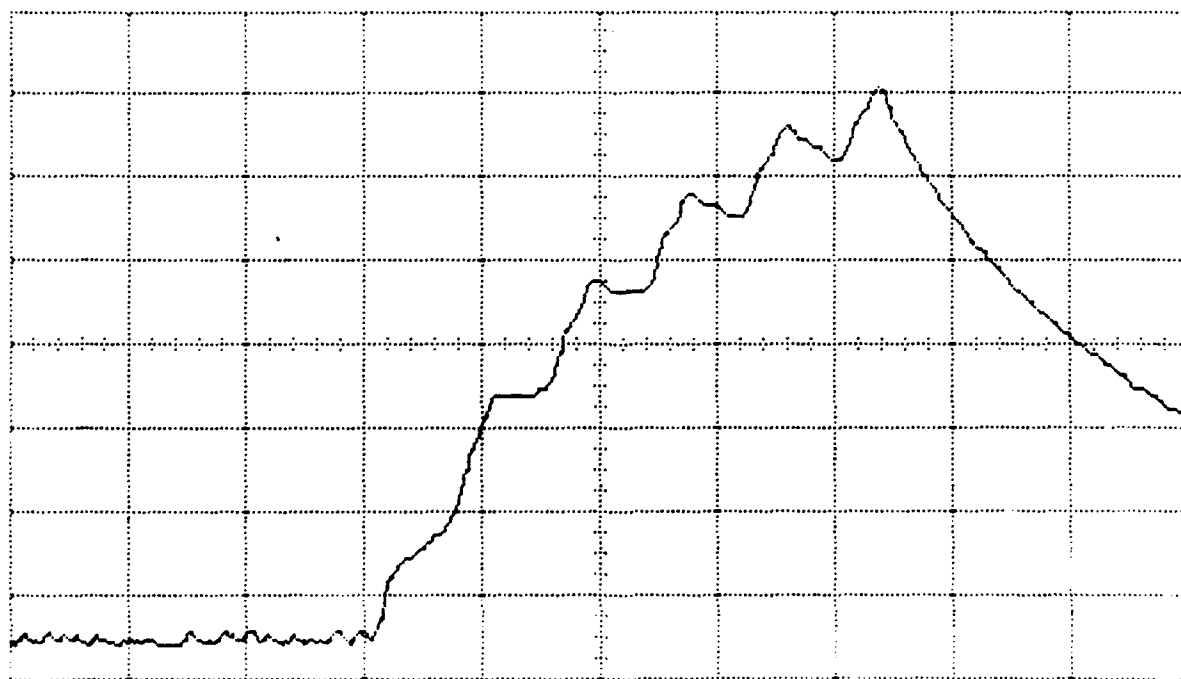
Fig.3 "Write and erase" optical logic operation. (a) The schematic of the experimental set-up, A1 and A2 are apertures, BS is beam splitter, (b) reflected signals from each etalon pumped separately, (c) reflected signal from both etalons being pumped showing "write" and "erase" function.

Incidence

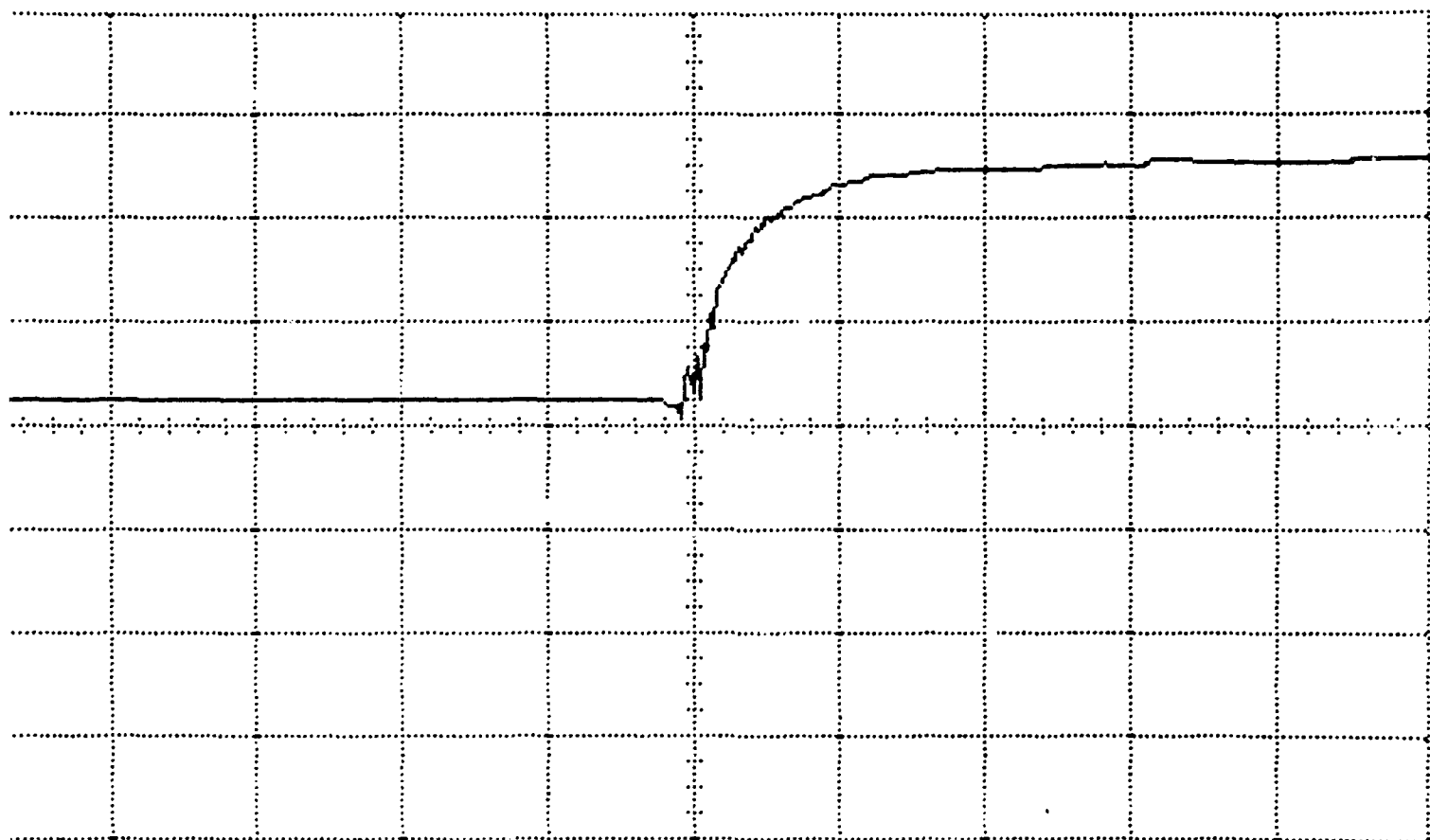


10 ms/div

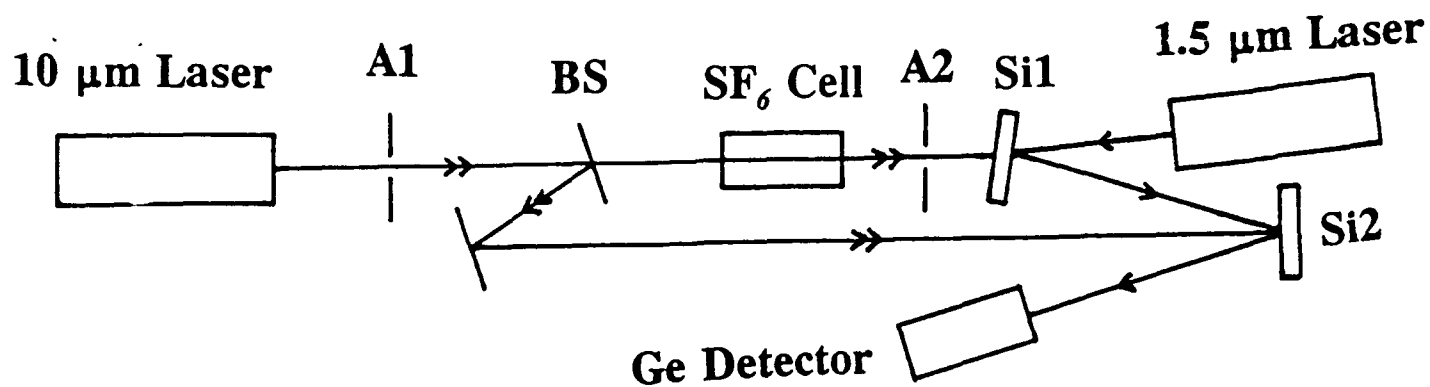
Reflection



10 ms/div

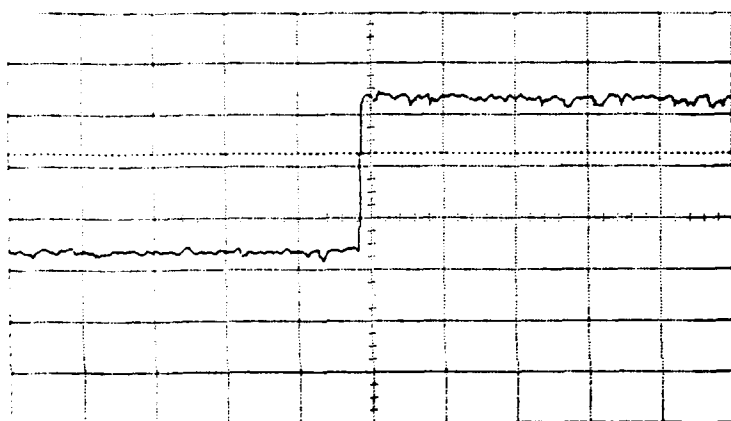


1 μ s/div



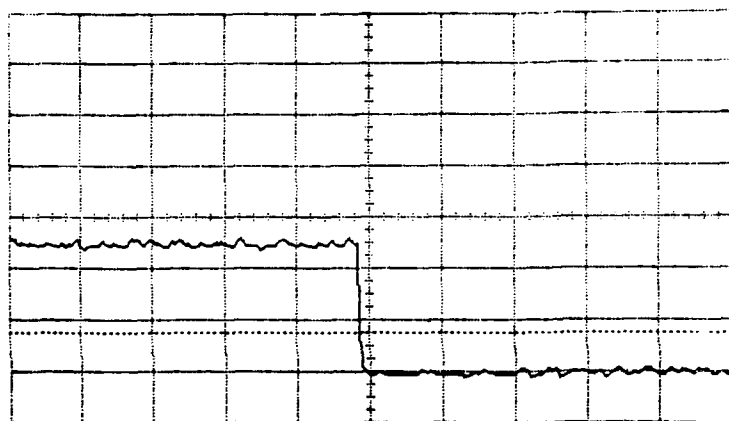
(a)

pump etalon 1 only



50 $\mu\text{s}/\text{div}$

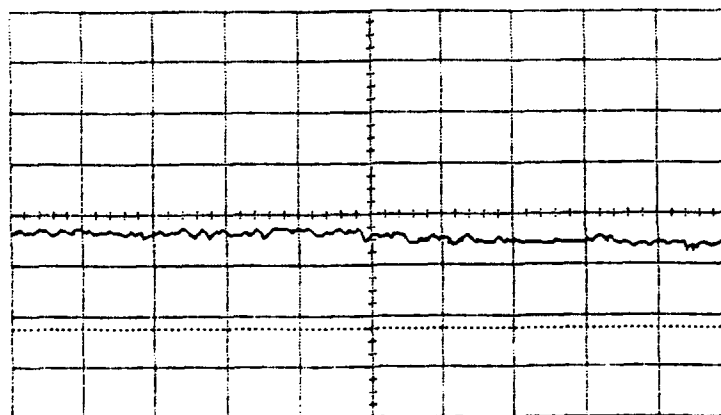
pump etalon 2 only



50 $\mu\text{s}/\text{div}$

(b)

pump both etalons



50 $\mu\text{s}/\text{div}$

(c)